Signatures of TeraGauss Magnetic Fields in X-ray Pulsar Spectra

by

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The Her X-1 Spectrum: A Measure of the Field near the Magnetic Poles of a Neutron Star

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Elihu was the first to suggest that the roll over at tens of keV that is now ubiquitous in X-ray pulsar spectra was the result of the anisotropy in scattering of photons from a highly magnetized plasma. This early analysis led to an estimate, albeit without error bars, of 10^{13} Gauss.

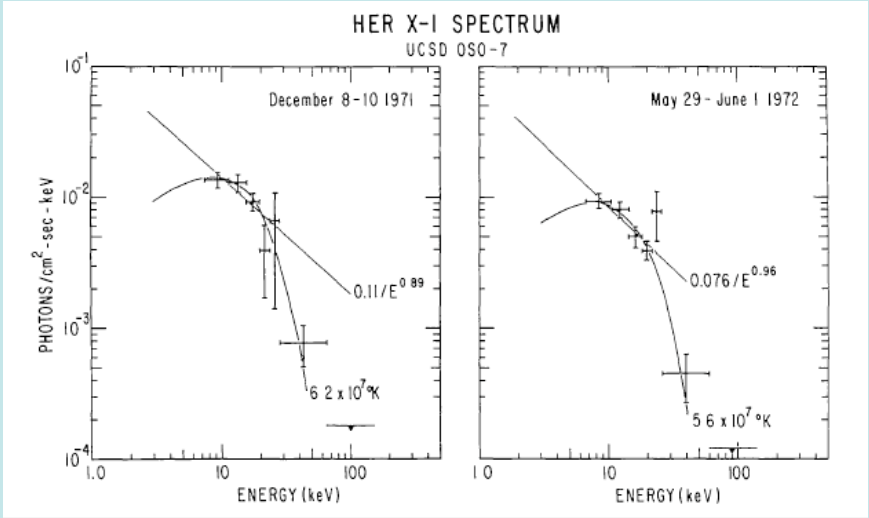
What was known for X-ray pulsar spectra in the early 1970's?

UHURU: "The spectrum appears to be very flat, with a best-fit power-law energy index of 0.0..." Giacconi et al. 1973

OSO-7: MIT α = 0.6±0.15 Clark et al. 1972

OSO-7: UCSD "... a change in slope near 25 keV (fig. 2) can be approximated analytically by a blackbody spectrum" Ulmer et al. 1973

The earliest indication of a roll over of a power law spectrum at ~25 keV

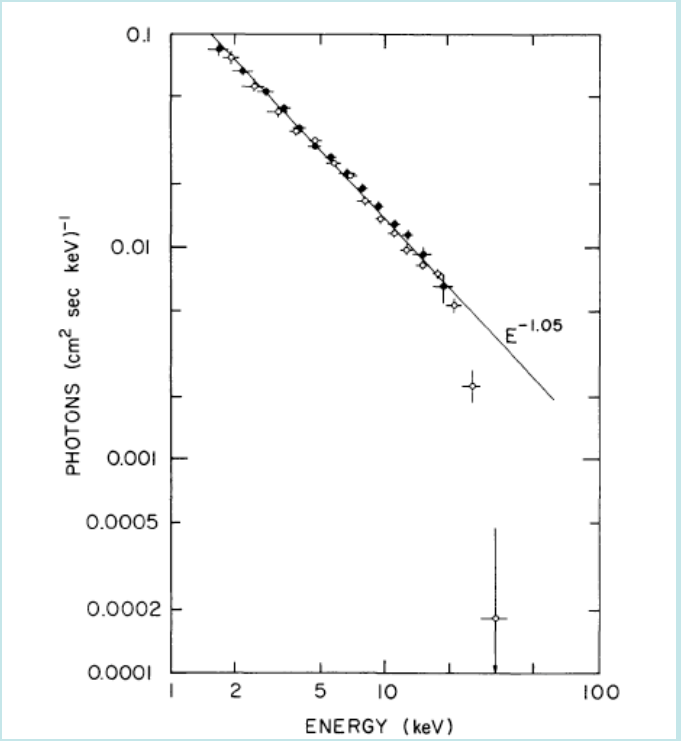


Ulmer et al. 1973

Spectrum of Her X-1 from the GSFC rocket flight of October, 1973

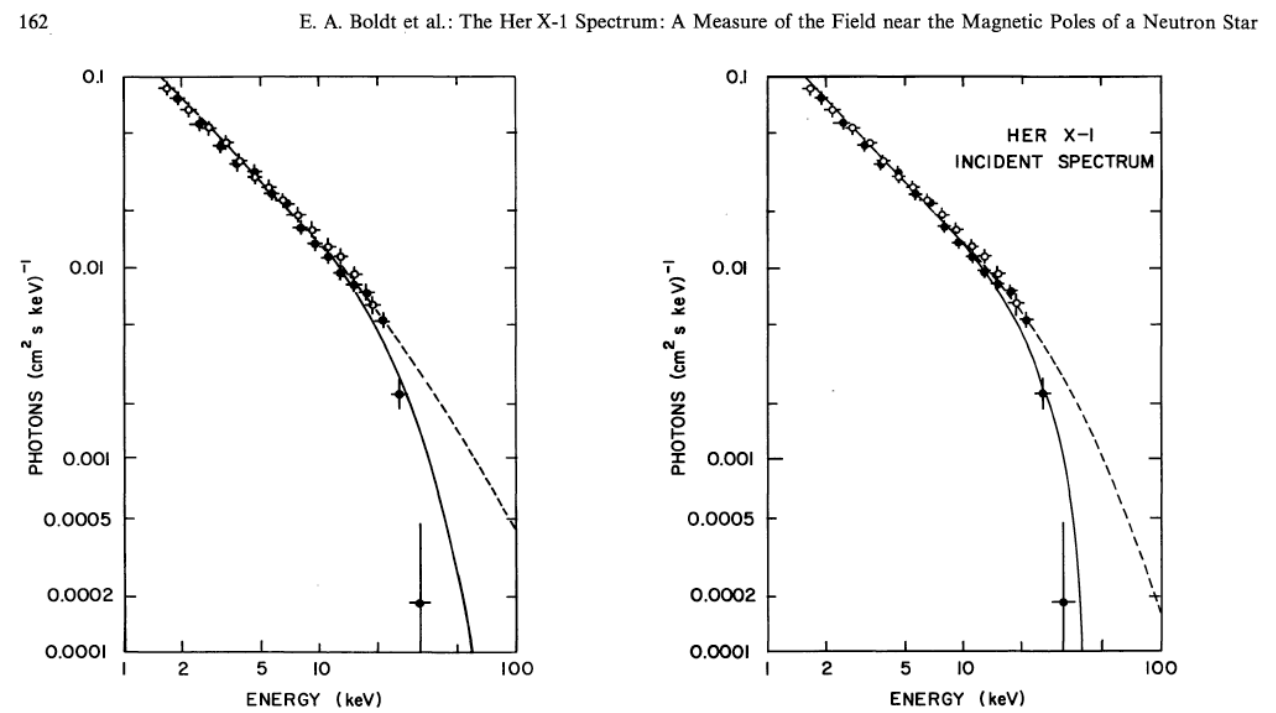
Elihu's Introductory Paragraph:

Basko and Sunyaev (1975) and Tsuruta (1974) have described how the pencil beaming of X-radiation necessary to explain the Her X-1 pulsar could arise from the anisotropy in scattering of photons from a highly magnetized plasma. In this communication, we show that the energy dependence of such scattering could also induce a spectral distortion adequate to explain the remarkably sharp high energy cut-off (at ~ 24 keV) in the Her X-1 pulsar spectrum previously reported by us (Holt et al., 1974).



Holt et al. ApJ, 190, L109, 1974

Elihu's analysis

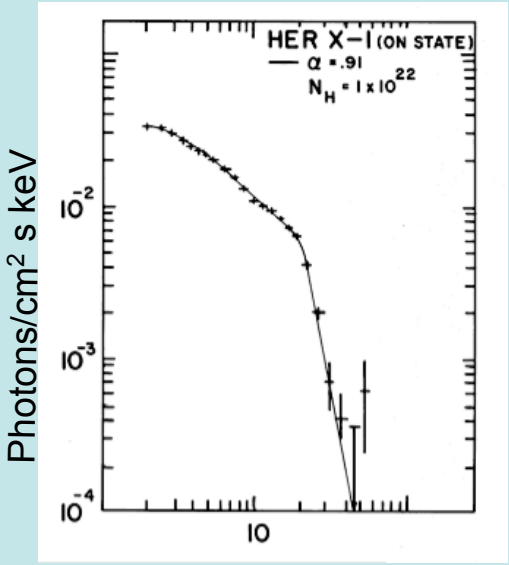


He followed the Basko & Sunyaev (1974) description of accretion onto a highly magnetized neutron star.

He concluded that the spectrum of the emerging unscattered beam depends mainly upon the nuclear mean free path optical depth and the magnetic field value, and that the detailed structure of the source with respect to the optical depth plays a minor role.

OSO-8 Observations of Her X-1 in August, 1975

Confirmation of the overall picture of a power law continuum that transitioned at ~20 keV to an exponential shape with E_F~7 keV (Becker et al. 1977).

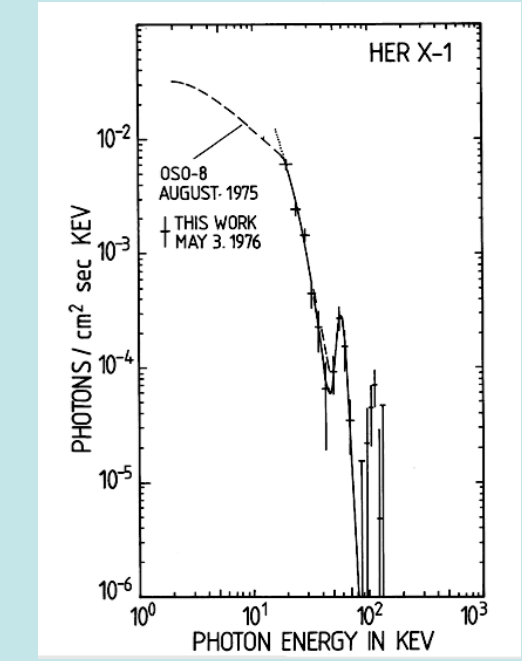


Garching/Tübingen Balloon Observation of Her X-1 in May, 1975

Discovery of the first "cyclotron line" in the pulsed flux from Her X-1 (Trümper et al. 1977).

Initially interpreted as an emission line at 58 keV on top of an exponentially falling continuum with kT=7.9 keV (Trümper et al. 1978).

We now know the feature is "absorption-like", and described by cyclotron resonance scattering.

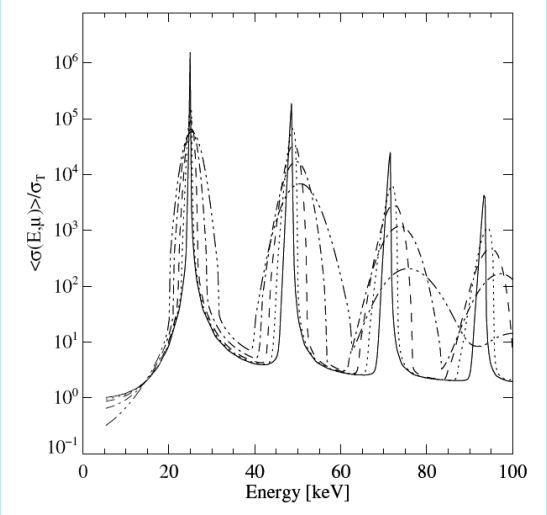


Cyclotron Resonance Scattering Features (" Cyclotron Lines")

Since the discovery by Trümper et al., it has become apparent that the spectral feature is due to cyclotron resonance scattering which produces an absorption-like feature.

The centroid energy yields the only known, direct measurement of the surface dipole field of a neutron star:

$$E_{cyc} \approx 11.6 \text{ keV} \times B \text{ (in units of } 10^{12} \text{ Gauss)}$$



Today we have measured one or more CRSFs in ~20 out of 66 accreting X-ray binary pulsars. The range of inferred magnetic field values ranges from 1.2 to 4.3 x 10^{12} Gauss.

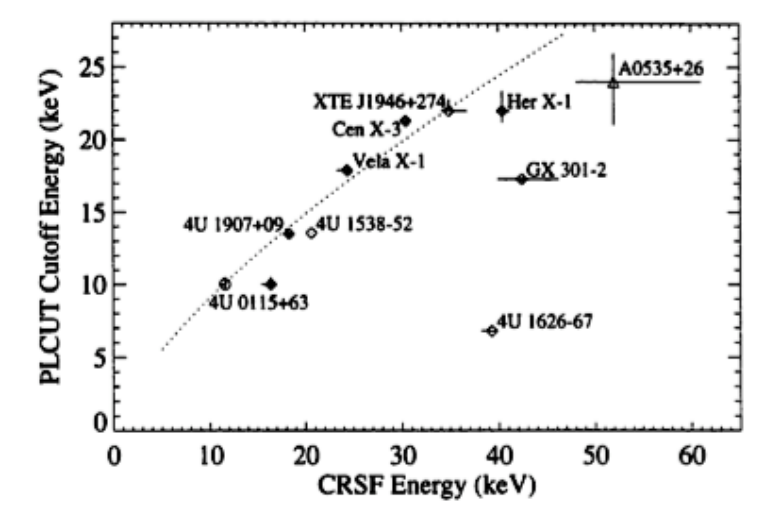
Fundamentals and harmonics are seen in 4 sources with 4U0115+63 having 4 harmonics detected.

Elihu's Prediction: Cut-off Energy ∝ Magnetic Field Strength

Elihu's work predicts that the cutoff energy should scale with the magnetic field strength, or expressing it as a cyclotron energy,

Measurements with RXTE show this to apply in general, but not in detail.

Mihara and collaborators and Staubert et al. have shown that mass accretion rate can also affect the observed cyclotron line energy.



Coburn PhD Thesis 2001

Modeling of the Physics of the Accretion Column

Modeling the full physics of accretion onto the magnetic pole(s) of a neutron star has been a challenging task.

Simple slab or column geometries have made way for settling mounds and accretion columns.

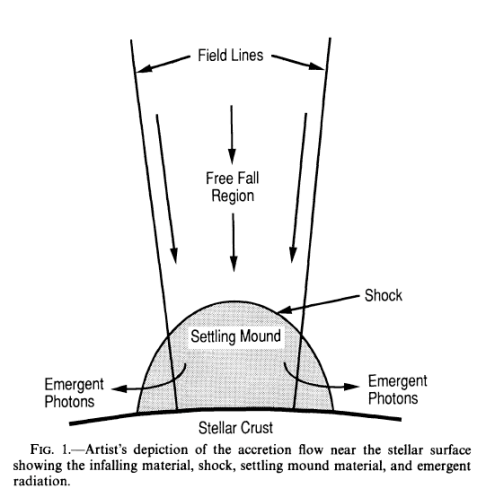


FIG. 1.—Artist's depiction of the accretion flow near the stellar surface showing the infalling material, shock, settling mound material, and emergent radiation.

Burnard, Arons & Klein (1991)

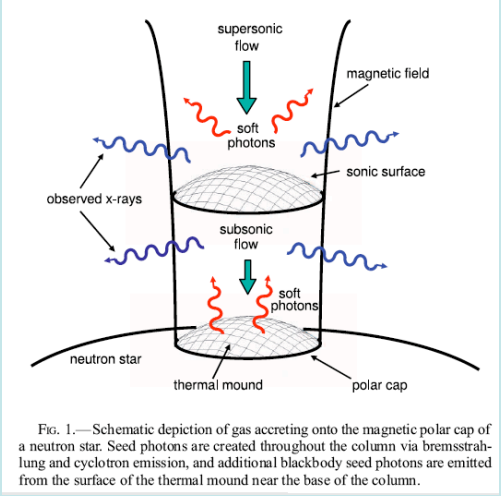


FIG. 1.—Schematic depiction of gas accreting onto the magnetic polar cap of a neutron star. Seed photons are created throughout the column via bremsstrahlung and cyclotron emission, and additional blackbody seed photons are emitted from the surface of the thermal mound near the base of the column.

Becker & Wolff 2007

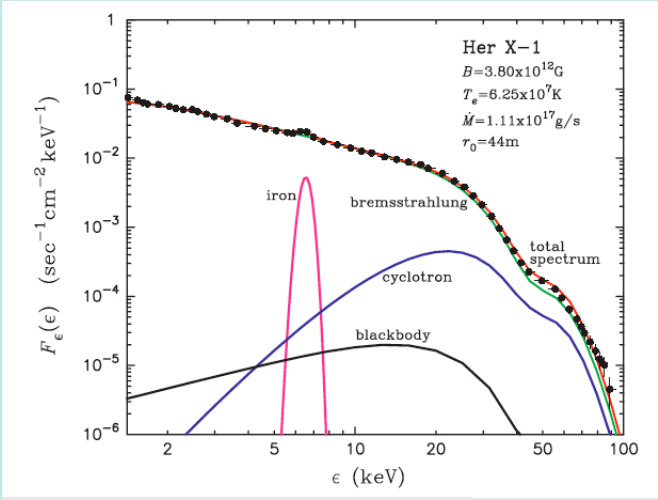
Including teraGauss magnetic fields adds to the complexity of the modeling the radiation transport.

Recent Advancements in Modeling the Continuum

Efforts by Becker & Wolff are beginning to generate predictions for the continuum shape based upon physical processes.

Model shape is defined by physical parameters, such as plasma temperature and accretion rate.

Aspects of radiation scattering in teraGauss fields needs to be included, especially consideration of the extraordinary mode interactions.



Modern Modeling of the CRSF

Modeling the radiative transfer in the accretion column has involved three approaches:

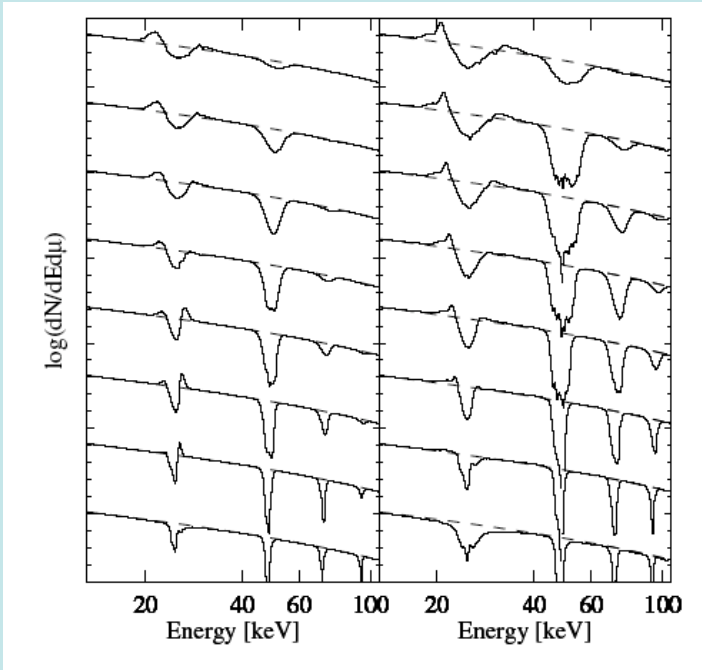
1) Solving finite difference equations by Nagel (1980, 1981), Nagel & Mészáros (1985) and Nishimura (2003, 2005).

2) Monte Carlo simulations by Yahel (1979), Wang (1989) and Schöherr et al. (2007) based upon Araya & Harding (1996, 1999, 2000).

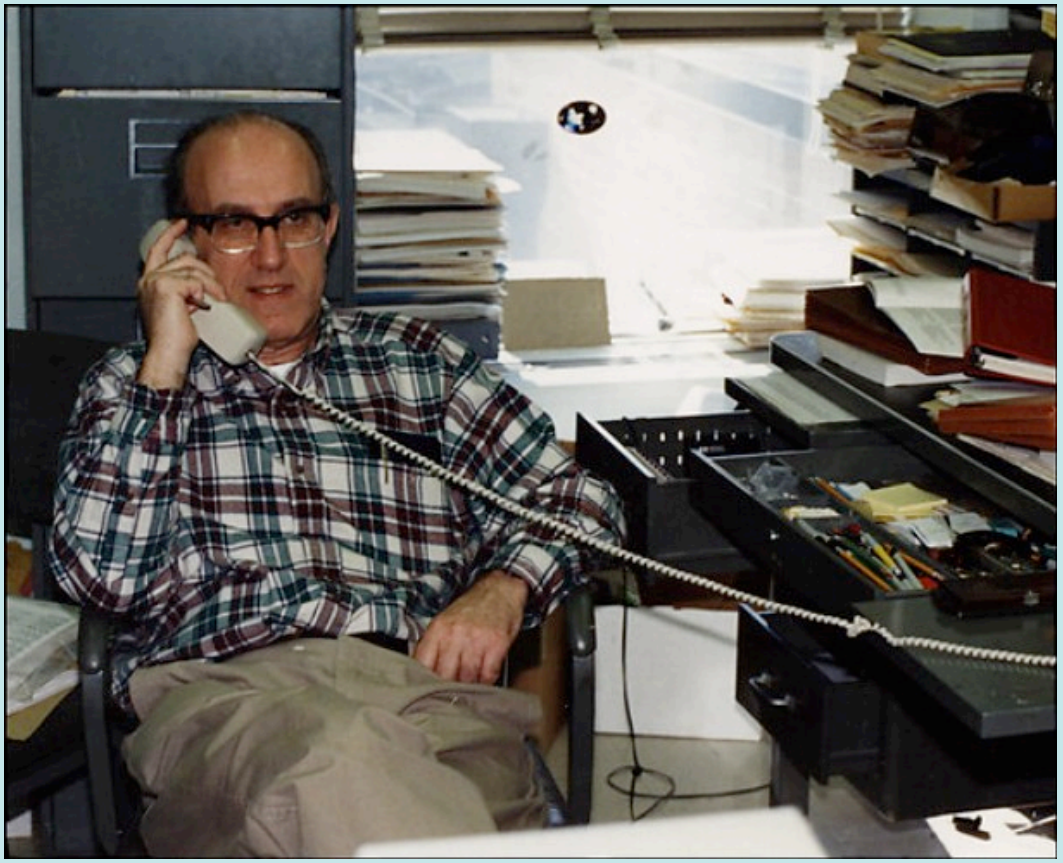
3) Radiation dominated shocks by Becker & Wolff (2007)

Only the first two generate estimates of the CRSF energy and shape.

Cyclotron Fundamental and Harmonic Line Profiles



Schönherr et al. (2007)



Elihu was an inspiration to all of us who had the good fortune to know him and work with him. He was a man of science, who was fascinated by all the new results flowing through Goddard, whether it was the interstellar medium, the diffuse X-ray background, searching for Sunyaev "chirps" from black holes, or the highest energy cosmic rays. We miss him already.